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AIRCRAFT ENGINE/APU FIRE EXTINGUISHING SYSTEM DESIGN MODEL (HFC-125)

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May 1997

FINAL REPORT FOR PERIOD OCTOBER 1992 TO APRIL 1997

Approved for public release; distribution unlimited

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AIR VEHICLES DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542

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This report documents a design model developed to facilitate the sizing of aircraft on-board fire protection systems with HFC-125, an environmentally acceptable substitute for Halon. The model was developed using empirical data from the Halon Replacement Program for Aviation and supplemented with other sources. The preliminary sizing of extinguishant containers and certification criteria, where relevant, is accomplished by the use of this model.

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LIST OF ACRONYMS

AIRFLOW	Exterior airflow rate (knots) flowing over the damage area in flight
AIRT	Maximum ventilation air temperature in the nacelle or APU during operations (°F)
APU	Auxiliary power units (APUs), which provide ground, supplementary or emergency power
Clutter	Components, equipment, structural members, such as in dry bays
Dry Bay	Wing leading/trailing edges, landing gear, avionics, and weapons bays, etc.
Engine Nacelle	Region surrounding the exterior of the jet engine case and shrouded by an outer cover and typically ventilated
°F	Degree Fahrenheit
FAA	Federal Aviation Administration
Free Volume	Free volume (ft^3) of the dry bay protected (minus clutter)
Ft	Feet
FUEL CONSTANT	Coefficient to account for presence of JP fuel, hydraulic fluids, or oil
Halons	Halogenated Fluorocarbons
Halon 1301	Bromotrifluoromethane
HEI	High explosive incendiary
HFC-125	Pentafluoroethane
Kts.	Knots
Lb.	Pounds (force)
Lbm.	Pounds (mass)
MASS	Extinguishant mass estimated for extinguishment (lb.)
ODC	Ozone depleting chemicals
psi	Pounds per square inch
Primary Fire Zones	Aircraft components where a failure in a flammable fluid system can result in ignition on a normally hot component surface, initiating a fire
Rough Nacelle	Nacelles with ribs less than 6 inches protruding into the nacelle
Sec	Second
SHOT ANGLE	Impact angle of the projectile into a dry bay with respect to the horizon (vertical = 1; horizontal = 0)
V	Free volume of nacelle or APU (subtracting volume due to internal components) (ft^3)
$\dot{W}_a$	Internal air mass flow rate in the nacelle or APU during operations (lb./sec)
$\dot{W}_{ACTUAL}$	Actual maximum air mass flow rate (no experimental bounds) (lb./sec)
WL	Wright Laboratory
WPAFB	Wright-Patterson Air Force Base
X_e	Certification Design Concentration

PREFACE

The use of halons, as well as other halogenated fluorocarbons, was determined recently to be associated with the destruction of Earth's ozone layer. Production of the halons was stopped in the United States by Presidential decree on 1 January 1994, and no new procurements requiring the use of ozone depleting chemicals (ODCs) were allowed by the Department of Defense after 1 July 1993. The Air Force announced in 1992 that their new F-22 fighter aircraft in development would not use ODCs and would have a "non ozone depleting solution" for aircraft fire protection by the 1995 time frame. The other U.S. military services made similar policies and took similar action. As a result, the Halon Replacement Program for Aviation was initiated by the U.S. Air Force Wright Laboratory, in collaboration with the U.S. Navy, Army and Federal Aviation Administration, to develop and demonstrate the best available substitutes for halons for aircraft dry bay and engine nacelle applications that could meet the timeframes described previously. In addition to the F-22, the Navy V-22 and F-18 E/F fighters, and the Army RAH-66 Commanche helicopter needed urgent identification of an appropriate substitute. The program was expanded in scope to meet the needs and requirements of aircraft dry bay and engine nacelle applications for all military and commercial aircraft.

Generic and reconfigurable engine nacelle and dry bay mock ups were used that could be made to represent the wide range of aircraft fire zone configurations, as well as limited experiments on APU fire simulators. Statistical experimental design techniques were used to translate the experiments representing a subset of all the possible combinations of fire zones and scenarios into an analysis and determination of the extinguishant with the best firefighting performance (based upon experimentation) on average for all of the fire zone conditions possible. Using this approach, HFC-125 was chosen as the best extinguishant for subsequent development of a design criteria by a tri-service representative group. This decision also factored in other data and experimentation on the extinguishants' storage and discharge characteristics, toxicity and materials compatibility traits. Once this decision was made, additional experiments were performed to develop a more precise model, again using statistical experimental design, for HFC-125 that would facilitate the sizing of extinguishing systems using it for various aircraft engine nacelle and dry bay applications. This process has been completed, and the design formulas and criteria have been established and are reported in this document.

EXECUTIVE SUMMARY

During the fire-extinguishing experimentation portion of the program, special procedures were followed in both the process of determining the final successful extinguishant value and by using replication of the experiments to assure a statistical fielded success confidence rate of extinguishing at least 88 to 90% using the derived model to predict required quantities of extinguishant for the simulator under various conditions. This compares favorably with the field experience of a 60 to 80% success rate, depending on the platform, of existing engine halon systems on aircraft currently. This predictive model was verified by performing later tests with the simulator set up to replicate the actual conditions of several aircraft currently in development, and the model exhibited a 90-100% effectiveness in repeated tests.

A regression model was also made of the concentration data collected in Phase II of the experimental program. It was decided to use the peak concentration measured at the fire point during discharge as a conservative representative value. It was also determined during supporting research performed by the National Institute of Standards and Technology that a one half second duration time would be a conservatively sufficient "dwell time" for the extinguishant at the required concentration under virtually all realistic operating conditions (although shorter times may be permissible under certain conditions, which will be studied further). The regression model developed for the concentration data was observed to conservatively slightly overpredict the required concentration shown by experiment for required concentrations below 25%. With these extra conservative factors accounted for, the derived predicted concentrations are expected to provide a high degree of confidence and success rate in use, while being customized for the demands of each application and verified with full-scale realistic fire experiments. This customization was performed to offset some of the potential weight penalties which may accompany systems using HFC-125.

The sizing formula (used to estimate the expected extinguishant mass required to meet certification standards) features a quantity $Xe/(100-Xe)$ in the second term of the formula (Xe being the required concentration of extinguishant), which is not present in the original halon formulas. In actuality, this term was dropped in the original formulas because the quantity approaches Xe in value for small values of Xe (such as 6 for halon), but doing so introduces some error. This quantity becomes more pronounced as Xe becomes larger, as is the case for HFC-125. This value accounts for the fact that when computing an effective concentration in a bay, the ratio must assess the volume of extinguishant versus the total mass in the compartment, which includes the total of the given air mass and the extinguishant introduced. In this situation, the mass required for 12% would require more than twice the mass to achieve 6%, with the mass requirement rising sharply as the required concentration increases. For this reason, this term must be accounted for with the increased extinguishant concentration requirements of HFC-125 over halons. This sizing model also must presume optimal mixing, so less efficient distribution systems will require higher masses to achieve the required concentration simultaneously for a half second during certification, with the designer having the option of accepting higher mass requirements or modifying and improving the distribution system.

This design model process will specify required concentrations in the range from 14.5% to 26%, depending upon the operating conditions.

1.0 INTRODUCTION

Fire-extinguishing systems are used on military and commercial aircraft to protect engine nacelles (the region surrounding the exterior of the jet engine case and shrouded by an outer cover, and typically ventilated) and dry bays (which can include wing leading/trailing edges, landing gear, avionics, and weapons bays). These systems are fixed in configuration and activated remotely to totally flood the compartment in question with fire extinguishant. Cargo bays are typically protected on many commercial aircraft with such "total flooding" systems, but with rare exception military aircraft are not (rather relying on the use of portable extinguishers) and, thus, will not be discussed in this document. Auxiliary power units (APUs), which provide ground, supplementary or emergency power, are also frequently protected using such systems, either as stand-alone units or in conjunction with the engine nacelle fire-extinguishing system.

Most fire-extinguishing systems use halogenated fluorocarbons, or "halons", as the fire-extinguishing fluid. Depending on the time period an aircraft was constructed, its engine nacelle fire-extinguishing system might have either Halons 1011, 1202, 1211 or 1301. The systems using Halons 1011, 1202, 1211 use a series of tubes in the fire zone perforated with small outlet holes to discharge the fluid in the form of a mist, to mix and disperse in the fire zone. The latter and most recent halon in use, Halon 1301, quickly assumes a gaseous state upon the discharge and subsequent release from pressurized containment, thereby filling compartments effectively with only a simple open tube at one or more selected locations in the fire zone. All of these engine nacelle systems are "certified", or approved in a given design configuration for a particular fire zone application and aircraft. The current specifications for Halon 1301 require a minimum of 6% concentration by volume in air be present simultaneously at all points in the engine nacelle for a minimum of 0.5 seconds. This specification is verified by experiment under realistic conditions. Dry bay fire protection systems, by contrast, are a new concept that will be fielded on selected aircraft in production now or in the future that warrant its use due to the combat threat environment and the mission profile of the aircraft. These systems have been verified recently by actual live fire testing using ballistic threats to assure performance in the actual fire-extinguishing of such events.

The use of halons, as well as other halogenated fluorocarbons, was determined recently to be associated with the destruction of Earth's ozone layer. Production of the halons was stopped in the United States by Presidential decree on 1 January 1994, and no new procurements requiring the use of ozone depleting chemicals (ODCs) were allowed by the Department of Defense after 1 July 1993. The Air Force announced in 1992 that their new F-22 fighter aircraft in development would not use ODCs and would have a "non ozone depleting solution" for aircraft fire protection by the 1995 time frame. The other U.S. military services made similar policies and took similar action. As a result, the Halon Replacement Program for Aviation was initiated by the U.S. Air Force Wright Laboratory, in collaboration with the U.S. Navy, Army and Federal Aviation Administration, to develop and demonstrate the best available substitutes for halons for aircraft dry bay and engine nacelle applications that could meet the timeframes described previously. In addition to the F-22, the Navy V-22 and F-18 E/F fighters, and the Army RAH-66 Commanche helicopter all needed urgent identification of an appropriate substitute. The program was designed to meet the needs and requirements of aircraft dry bay and

engine nacelle applications for all military and commercial aircraft. The program entailed screening a list of almost 600 potential candidate extinguishants down to 12 semifinalists for detailed experimentation and three finalists for full-scale engine nacelle and dry bay fire experiments using Wright Laboratory facilities. Generic and reconfigurable engine nacelle and dry bay mock ups were used that could be made to represent the wide range of aircraft fire zone configurations, as well as limited experiments on APU fire simulators. Statistical experimental design techniques were used to translate the experiments representing a subset of all the possible combinations of fire zones and scenarios into an analysis and determination of the extinguishant with the best firefighting performance (based upon experimentation) on average for all of the fire zone conditions possible. Using this approach, HFC-125 was chosen as the best extinguishant for subsequent development of a design criteria by a tri-service representative group. This decision also factored in other data and experimentation on the extinguishants' storage and discharge characteristics, toxicity and materials compatibility traits. Input was also obtained from the Technology Transition Team, which consisted of over 100 members of the operational community, including maintenance personnel, aviation fire extinguisher manufacturers, aircraft manufacturers, and government program managers of specific aircraft. Once this decision was made, additional experiments were performed to develop a more precise model, again using statistical experimental design, for HFC-125. This would facilitate the sizing of extinguishing systems for use in various aircraft engine nacelle and dry bay applications. This process has been completed, and the design formulas and criteria have been established and are reported in this document.

The intent of this program and the subsequent design guide is to retain an equivalent level of firefighting performance to the current halon systems, and the design guide formulas are configured to accomplish this level of performance. Much was learned over the course of the program that revealed the limitations of current halon systems under certain circumstances and new ideas on improved performance were discovered. However, the incorporation of such performance would increase the sizing and complexity of such systems over the current art and is beyond the charter of this program. Like the halon systems they replace, the new systems incorporating HFC-125 at this level of protection will not extinguish every imaginable fire condition created (and if so, it could not be verified via experimentation). However, much effort has gone into quantifying the level of performance of current halon systems (previously not known before except by the review of historical mishap data) and assuring the level of protection is preserved with new HFC-125 systems. In fact, more sophisticated techniques have emerged and are used in this design guide to better customize the design output to the particular application to prevent overdesign of systems, while retaining the general historical approach and philosophy of designing and certifying systems and using unambiguous aircraft design data as input. It is interesting to note that the halon systems as currently designed and tested in the program simulations exhibited a performance of 80 to 100% effectiveness at fielded design quantities (with historical data revealing an overall 60-80% effectiveness) for engine nacelle applications, with the HFC-125 design guidance demonstrating a validated 80-100% effectiveness (and a predicted 88% plus ultimate effectiveness statistically). Systems designed using HFC-125 will generally require additional quantities to varying degrees (per application) than their halon counterparts for an identical application, **assuming an optimized halon system is used.** (It has been found that many fielded halon systems are not optimal in sizing, and the

estimate of installing a replacement HFC-125 container has resulted in much smaller size increase impacts than was expected.) As an example of potential size impacts, the current engine nacelle design guidance published here will result in design concentrations of 14.5 to 26% by volume (depending upon the fire zone configuration), as opposed to 6% for Halon 1301. As an estimate, this will translate into a roughly proportional increase in container volume in comparison to the ratio of design concentrations of HFC-125 and Halon 1301 (about 2.3 to 4.3 fold increase), and approximately 80% increase in extinguishant weight proportional to the volume increase. This increase in weight and space required has been planned and allocated for by aircraft now in design and production, but may pose challenges for those aircraft already designed for halon systems.

Details on the experimental program, test conditions, and results that created the data used to develop this design model are outlined in WL-TR-95-3039 (SURVIAC 95-010), "Halon Replacement Program for Aviation, Dry Bay Application, Phase I--Operational Parameter Study", September 1995, WL-TR-95-3077 (SURVIAC 95-011), "Halon Replacement Program for Aviation, Engine Application, Phase I--Operational Parameter Study", April 1997, and associated Phase II and III Wright Laboratory Technical Reports in publication as of May 1997. This report will only highlight specific details essential for the successful use of this design model.

This design model is being published in two versions. The first, "Aircraft Engine/APU Fire Extinguishing System Design Model (HFC-125)", contains only engine/APU relevant information, and is released for unlimited distribution. The second version, "Aircraft Engine/APU and Dry Bay Fire Extinguishing System Design Model (HFC-125)", features both distinct applications and is limited in distribution to DoD components and their contractors.

2.0 ENGINE NACELLES/AUXILIARY POWER UNITS (APUs)

2.1 Background

The engine nacelle is defined as the region surrounding the exterior of the jet engine case, shrouded by an outer cover, and typically ventilated. Auxiliary power units (APUs) are machinery units that provide supplemental, auxiliary, or emergency power to all or some subsystems of the aircraft.

2.1.1 Fire Zone, Design Issues

Engine nacelle fire protection systems have been commonplace since the middle of this century. These systems are designed to protect events such as ruptured or leaking fuel, hydraulic fluid, or oil lines within the nacelle, which can leak onto the hot engine case or accessory components and ignite, or catastrophic events such as thrown turbine blades that instantaneously rupture fuel sources or overheating components that can initiate fluid fire scenarios. The first step in such cases is to shut down the engine, once the proximity fire detector confirms a fire is present, and the pilot is satisfied that a true fire event has occurred. Even with the engine shut down and flammable fluid supply turned off, up to a minute or more of fuel and other flammable fluids flowing into the fire zone can occur, sometimes under high-pressure, depending upon the location and nature of the failure and the capability to remotely arrest the flow near the point of damage. Under these conditions, a supply of fuel can be maintained for a lengthy period to create robust fire conditions that, left unchecked, can heat and ignite severe metal fires or burn through surrounding structure and threaten the welfare of the aircraft, creating fire conditions in collateral areas before the fuel is drained, thereby weakening key structures. In addition, impacts into the engine nacelle by ballistic projectiles in combat can also create failure conditions and resultant fires (provided that the engine case is not penetrated, which could result in catastrophic engine failure becoming the more immediate threat).

The storage containers (or "bottles") of fire extinguishant for engine fire protection systems are typically remotely located from the engine nacelle (although not always)--sometimes up to fifty or sixty feet away from the engine nacelle itself. The bottle is typically activated, at the initiation of the pilot, by the firing of a pyrotechnic squib that severs a rupture disk and releases the contents of the bottle. The extinguishant must then travel some distance through a series of plumbing to the nacelle in question. A bottle may be plumbed to more than one engine nacelle, and some configurations will cross-feed two different bottles to the same two nacelles to provide "two-shot" protection to the nacelle needing extinguishment. Once the extinguishant reaches the nacelle, it discharges either as a gas at one or more remote locations in the nacelle (for high volatility extinguishants such as Halon 1301) or through a series of perforated holes in a complex network of distribution tubing within the nacelle (such as with low volatility extinguishants Halon 1202, 1211, and 1011). The systems are designed to provide a uniform concentration of at least 6% by volume simultaneously at all points in the nacelle for at least one half second. This quantity is based upon experience in experiments performed in the 1950s and 60s by the Civil Aviation Administration, U.S. Air Force, U.S. Navy, and collateral investigators that examined the effects of varying nacelle conditions and configurations on the success of

extinguishment, although the detailed history and hierarchy of data that led to the final Halon design specifications in use is difficult to define precisely.

APUs are used to provide supplemental, auxiliary, or emergency power to all or some of the subsystems of the aircraft, either on the ground or in flight. These units function and generate power independently from the normal aircraft engine systems. The power units may be miniature turbines or other power generating equipment, but are typically smaller than the normal jet engine propulsion systems. These compartments must be protected against potential fires, since the possibility of fuel, hydraulic fluid, or oil leakage onto the hot power unit and equipment or catastrophic unit failure can create fire scenarios just as in the engine nacelles. For many military aircraft, the engine fire protection system is plumbed to be alternatively used in the auxiliary power unit compartment, since in most cases the engine fire protection system's capacity is more than adequate for the smaller volume of the APU bay. In some cases, however, the APU compartment may have a larger free volume than an individual engine nacelle or otherwise require a greater quantity of extinguishant than the nacelle, so great care must be taken to assure that sufficient capacity is designed for either use. APU compartments can be ventilated, so provision must be made for dilution of extinguishant by ventilation airflow during discharge. In many cases, however, the ventilation system is designed to be closed during discharge, hopefully sealing off the compartment. For many military transport and most commercial aircraft, an independent fire protection system is designed for a remote APU compartment, which may be located within the cabin or cargo section, or in the tail section. These systems must then be designed separately from engine nacelle systems.

Engine nacelle and APU fire protection applications differ from dry bay applications, such as wing leading/trailing edge bays, landing gear, avionics, weapons and other bays, in one significant aspect. Engine nacelle and APU compartments are designated primary fire zones, since merely a failure and leak in the flammable fluid system can result in ignition upon the hot operating components of the power unit and result in a fire. Dry bays, in contrast, require both an event to release a flammable fluid source and the creation of an ignition source. They can result primarily from ballistic penetration into military aircraft in combat or by electrical shorting in avionics/electrical equipment, or by the initiation of internally stored munitions. This difference is used to distinguish between the two categories of potential fire zones, and can be used to determine which design approach is relevant in this design model for a given application (if both engine nacelle/APU and dry bays are included in this version).

The traditional approach used to design halon engine fire-extinguishing systems is to design and certify in experiment that a minimum concentration at 6% by volume can be maintained uniformly in the engine nacelle for at least one-half second, with design formulas used to estimate the extinguishant mass that will be sufficient to meet this criteria.

The original data or rationale that led to the configuration of these formulas is uncertain. A conceptual model, which assumes a one second discharge time (a requirement) from the reservoir and perfect mixing of the extinguishant with the incoming ventilation air to maintain the 6% concentration and account for dilution of the extinguishant in the nacelle due to ventilation air for the one second duration, will approximate the primary formula. This formula

features a term that accounts for the existing volume of the nacelle and one for the dilution due to a fixed mass of air displaced in the nacelle at the rate of airflow ventilation during the portion of the discharge period in which certification occurs. Two accompanying formulas are used alternatively in lieu of the primary formula if the nacelle has ribs and the ventilation airflow is above 1 lb./sec or if the nacelle is a "deep frame" nacelle with deeply protruding structural members. The exact set of data used to derive these formulas empirically is uncertain, but some data from the 1940s through 1960s suggests their origin. Their modification to the primary formula is either to increase the coefficients of the terms or to offer a volume-specific formula as an alternative. One of the modifications, in terms of final value, is the factor of three added to the original formula to account for "rough nacelles" (those with ribs less than six inches protruding into the nacelle) under airflow greater than 1 lb./sec. A source of data from the earlier time period suggested a growth of up to a factor of three in extinguishant required in full-scale nacelle fires at very high air mass flow rates, but the additional required extinguishant was not observed until airflow levels around 5 lbm/sec, which is above the operating range of most aircraft in use today. For these reasons, the new formulas will not attempt to explain or replicate these variations but will rely on the single derived sizing formulas. In the experimentation used to derive the new formulas, frame members in the experimental simulator protrude with significant depth and approach a worst case scenario. In any event, these sizing formulas only give a first approximation of the expected mass requirement for certification, both for the old formulas for halon to achieve 6% and the new formulas for HFC-125 to achieve its required concentration. Sizing adjustments may need to be made during certification tests to account for inefficient distribution in either scenario. The formulas also serve as an approximation of mass requirements when performing trade studies of various alternatives while the aircraft is in design. It has been observed that some existing halon systems in use have been sized to create certification concentrations far above the 6% and may be considered oversized. This may be attributed to confusion previously over whether the sizing formulas (which can sometimes result in large quantities) or the 6% concentration standard took precedence in design requirements. The designer's expectation of the requirement preferring the more conservative estimation led to systems being sized to the larger quantities in may cases. In those applications and design configurations, a properly sized HFC-125 system may be competitive in size to the existing halon system. Concern should not immediately arise if sizing values are suggested from the design model that are comparable to the existing system and, thus, be counterintuitive in terms of performance expectations. The certification process itself may modify somewhat the final extinguishant mass requirement, since the sizing formula presumes optimal distribution. The design concentration calculated for HFC-125 in a given installation using this model will be the actual certification standard to approve a system, with the sizing formulas used to assist in estimating mass to meet certification requirements.

In summary, the approach used to design HFC-125 systems is virtually identical to that used to size existing halon systems for engine nacelle applications. The only substantive difference in the new approach is the opportunity to derive a customized design concentration for certification and a simplified bottle sizing estimation approach. This process will be described in detail in a later section.

2.1.2 Development Process

2.1.2.1 Experimental Technique

Wright Laboratory built a reconfigurable, full-scale engine nacelle experimental simulator at Wright-Patterson Air Force Base, and experiments using it were performed at the Aircraft Engine Nacelle Test Facility at Wright Laboratory. Data were collected on all the extremes of engine nacelle configurations and operating conditions of DoD and commercial aircraft. The simulator was designed to accommodate almost all of these configuration extremes, while the facility was adapted to replicate virtually all of the operating condition extremes. Up to 15 configuration or operating condition variables were assessed simultaneously, as well as interactions between the variables, during experimentation. To accomplish this process within the required budget and schedule, a statistical experimental design process was used, featuring fractional factorial orthogonal experimental matrices. From these initial experiments, a subset of variables observed to be significant in impacting the quantities of extinguishant required were evaluated further in greater detail, using the final extinguishant candidates under consideration. In conclusion, an even larger database was created using the selected final extinguishant, HFC-125, with more incremental variations in the significant variables evaluated. A regression model was developed from the empirical data to predict extinguishant quantities as a function of the test simulator configuration and operating conditions in the simulator.

The next phase was to replicate the range of configurations and operating conditions in the simulator during the first phase, with discharges of various masses of extinguishant. A concentration probe was used to measure the concentration at the location of the fire during discharge, although no fire was initiated (fortunately, existing equipment to certify halon systems has been calibrated to also measure HFC-125). The purpose of this process was to "translate" the mass required under given conditions to extinguish a fire to the concentration levels measured at the location of the fire, under "no fire" conditions (such as during certification), but under identical operating conditions. Data were collected on concentration measurements for a wide range of operating conditions, configurations and mass quantities, and regression analysis was performed to develop a model that predicted required extinguishant concentrations for given conditions and mass quantities. This allows one to determine an optimal customized design concentration for a given application and conditions.

Experiments were also performed in an experimental simulator to represent APUs. It was found that extinguishant quantities designed according to guidance for engine nacelles were more than adequate to extinguish APU fires under the simulated conditions. In the limited test series allowable due to time and funding constraints, it was determined that applying the engine nacelle design approach to APU compartments would be a conservative approach. When one is designing a system used to protect both an engine nacelle and a separate APU, care must be taken to design the system for the larger of the two requirements, and independent sizing estimations should be performed for both applications.

2.1.2.2 Analysis

During the fire-extinguishing experimentation portion of the program, special procedures were followed in both the process of determining the final successful extinguishant value and by using replication of the experiments to assure a statistical success confidence rate of extinguishing of at least 88 to 90% using the derived model to predict required quantities of extinguishant for the simulator under various conditions. This compares favorably with the field experience of a 60 to 80% success rate, depending on the platform, of existing engine halon systems on aircraft currently. This predictive model was tested by performing later tests with the simulator set up to replicate the actual conditions of several aircraft currently in development, and the model exhibited a 90-100% effectiveness in repeated tests.

A regression model was also made of the concentration data collected in Phase II of the experimental program. It was decided to use the peak concentration measured at the fire point during discharge as a conservative representative value, since other related ongoing research in determining an effective equivalent extinguishant value during the concentration-time profile coupled with a required duration was inconclusive at this time in deriving a user-friendly single required value approach. It was also determined during supporting research performed by the National Institute of Standards and Technology that a one-half second duration time would be a conservatively sufficient "dwell time" for the extinguishant at the required concentration under virtually all realistic operating conditions (although shorter times may be permissible under certain conditions, which will be studied further). The regression model developed for the concentration data was observed to conservatively slightly overpredict the required concentration shown by experiment for required concentrations below 25%. With these extra conservative factors accounted for, the derived predicted concentrations are expected to provide a high degree of confidence and success rate in use, while being customized for the demands of each application and verified with full-scale realistic fire experiments.

It was observed during fire-extinguishing experimentation that when hot operating engine case surface temperatures were simulated, reignition could occur on these surfaces due to residual fuel adhering to the surface or fuel continuing to be sprayed before being shut off. This phenomena was typically seen at surface temperatures at or above 1000°F and then only sparingly and without any reliable appearance. Adjustments were made in the program to account for this by controlling the fuel flow duration (thereby limiting the range of protected fuel system failure scenarios) to determine the limits of flow time where the Halon 1301 quantity, prorated in size to the volume of the simulator and using the most generous design quantity of fielded systems, would just keep the fire out. This approach was intended to replicate the given limited level of reignition protection offered by existing halon systems. Unfortunately, it was found that the probabilistic event of reignition greatly destabilized the extinguishing experiments and results due to lack of reliable repeatability in experimentation. Great effort was taken to accommodate this behavior statistically, and by using large data sets, but the phenomena could not be replicated repeatedly and reliably. In addition, regression models attempting to incorporate these data were poor predictors of actual experimental results, for both the experiments that exhibited reignition and those that did not. The mass values predicted for protection were also unacceptably high for any realistic application of such systems. It was also

observed that Halon 1301 experiments in the simulator, sized to existing halon specifications, failed to maintain extinguishment under these reignition events. **FOR THESE REASONS, THE DESIGN GUIDE HAS BEEN CONFIGURED TO PROVIDE PROTECTION FOR FIRE EVENTS NOT SUBJECT TO HOT SURFACE REIGNITION, AS IS CONSISTENT WITH THE PERFORMANCE OF EXISTING HALON SYSTEMS.** If hot surface temperatures cannot be avoided (such as with uninsulated bleed air ducts), the duration period required for the design concentration during certification may have to be expanded to the duration of time that the fuel will be expected to be in proximity to the hot surface. Under these conditions, the sizing estimation formula will not be sufficient to assess final sizing requirements.

The sizing formula (used to estimate the expected extinguishant mass required to meet certification standards) features a quantity *Xe/(100-Xe)* in the second term of the formula (Xe being the required concentration of extinguishant), which is not present in the original halon formulas. In actuality, this term was dropped in the original formulas because the quantity approaches Xe in value for small values of Xe (such as 6 for halon), but doing so introduces some error. This quantity becomes more pronounced as Xe becomes larger, as is the case for HFC-125. This value accounts for the fact that when computing an effective concentration in a bay, the ratio must assess the volume of extinguishant versus the total mass in the compartment, which includes the total of the given air mass and the extinguishant introduced. In this situation, the mass required for 12% would require more than twice the mass to achieve 6%, with the mass requirement rising sharply as the required concentration increases. For this reason, this term must be accounted for with the increased extinguishant concentration requirements of HFC-125 over halons. This sizing model also must presume optimal mixing, so less efficient distribution systems will require higher masses to achieve the required concentration simultaneously for a half second during certification, with the designer having the option of accepting higher mass requirements or modifying and improving the distribution system.

This design model process will identify required concentrations in the range from 14.5% to 26%, depending upon the operating conditions. Since the ratio of storage volume growth impact of using HFC-125 versus Halon 1301 is roughly comparable to the ratio of concentration requirements (due to the offsetting characteristics of molecular weight and liquid density), the expected volume of an HFC-125 system should be approximately 2.3-4.3 times the size of an <u>optimal</u> halon system for a given application. In many cases, when comparing to existing halon installations the growth will be much smaller, due to the oversizing of previous halon systems as is common in many cases. Since the HFC-125 is lighter per unit volume of liquid over halon, the weight increase should be roughly only 80% of the volume increase encountered.

2.1.3 Two Step Design Formula Process (Engine/APU)

The two step approach to determine the required design concentration for certification and estimate the necessary mass of extinguishant to meet certification requirements is quite simple, and in general consists of the following procedure:

(1) Calculate the design concentration required using the Formula E-1 in this design model, using relevant values of air temperature, air mass flow rate, and fuel type.

   a) If the range of air temperature and air mass flow rate vary considerably in the flight envelope, several combinations of relevant maximum air temperature and corresponding mass flow rates should be tried to assure the highest concentration calculation is achieved. In general, the application of the highest air temperature and minimum air mass flow rate (with acceptable data bounds) will give a conservative worst-case estimate, but could be a slight overdesign.
   b) For this formula the values input for maximum air temperature and air mass flow rate should never be outside the bounds relevant for the formula (100°F to 275°F and 0.9-2.7 lb./sec, respectively). If the actual maximum operating condition is outside of this bound, the closest extreme value should be used. The impact on the accuracy of the results has been shown in experiment to be minimal.
   c) If more than one flammable fluid is present in the engine nacelle or APU (such as hydraulic fluids or oils), use the highest fuel constant value corresponding to the fluids present. (For example, the fuel constant = 0.4053 for hydraulic fluid would be used if it is present, since it is the highest constant).
   d) If a single system protects both one or more engine nacelles and an APU, calculate the required concentration and corresponding mass for either application independently and use the higher of the two mass requirements.

(2) Calculate the expected extinguishant mass requirement, using the concentration calculated in (1), the volume of fire zone (nacelle or APU) and the <u>actual</u> air mass flow rate (even if outside the bounds considered in (1)).

(3) Design the extinguishant container capacity consistent with current design practice and use mass estimates in (2), for use in design trade-study comparisons and as a starting point for certification testing.

(4) Perform the certification discharge experiments (using existing Halonizer or Statham analyzer equipment as is used for halon systems to measure concentrations real-time, but recalibrated for HFC-125), with the criteria being the attainment of the design concentration calculated in (1) at all measurement points in the nacelle simultaneously for at least 0.5 seconds.

(5) If certification is not met, increase the container capacity or modify the distribution system to eventually pass certification.

2.2 Concentration (Xe) Estimation Formula

2.2.1 Background

The concentration calculated using formulas E-1 will be the concentration used for certification testing of a designed HFC-125 system for engine nacelle or APU protection. The traditional certification process, using a Halonizer or Statham Analyzer calibrated for HFC-125, will be used to assure that at least the concentration calculated by E-1 is present simultaneously at each measurement point in the nacelle for a minimum of 0.5 seconds. Formula E-1 can give a range of concentration values from 14.5 to 26%, expressed as a whole number (19.5 versus 0.195).

2.2.2 Design Formula

EXTINGUISHANT CONCENTRATION (ENGINE)--FORMULA E-1

$$\mathbf{Xe} = 21.10 + 0.0185\ \text{AIRT} - 3.124\ \dot{\text{W}}\text{a} + 5.174\ (\text{FUEL CONSTANT}) + 0.0023\ (\text{AIRT}) \times (\text{FUEL CONSTANT}) + 1.597\ (\text{FUEL CONSTANT})^2 \qquad \text{(E-1)}$$

Xe = Certification Design Concentration
AIRT (°F): maximum ventilation air temperature in the nacelle or APU during operations
$\dot{\text{W}}$a (lb./sec): internal air mass flow rate in the nacelle or APU during operations
FUEL CONSTANT: coefficient to account for presence of JP fuel, hydraulic fluids, or oil

THE VARIABLE RANGES PERMISSIBLE FOR INSERTION INTO FORMULA E-1 ARE:

AIRT	100-275°F
$\dot{\text{W}}$a	0.9-2.7 lb./sec
FUEL CONSTANT	
If JP fuel, use	0.3586
If hydraulic fluid, use	0.4053
If oil , use	0
If fire resistant hydraulic fluid (SKYDROL), use	0
(USE HIGHEST COEFFICIENT OF FLUIDS PRESENT)	

NOTE THE FOLLOWING LIMITATIONS:

- **Evaluate maximum engine nacelle/APU air temperature and corresponding air mass flow rates at various points in the flight envelope to determine the maximum necessary Xe (overall maximum air temperature and minimum air mass flow rate in flight can be used as conservative estimate).**
- **If value of actual air temperature or $\dot{W}a$ is outside bounds of permissible variable ranges, then input at allowable extreme closest to actual value (this impact on the effectiveness of calculated Xe has been shown in experiment to be minimal).**
- **If an engine nacelle and APU are both protected with a single system, determine required concentration and mass separately for both applications independently, then size for larger requirement.**

2.2.3 Concentration Duration For Certification

All measuring probes must measure at least Xe simultaneously for a minimum of 0.5 seconds.

2.3 Engine/APU Mass Estimation Formula

2.3.1 Background

Formula E-2 is a theoretically derived formula (not empirical) to estimate the mass of extinguishant required in storage in a system to pass the certification process with Xe calculated from Formula E-1. The formula was derived with similar principles to that used for earlier halon certification, and the formulas are similar in structure. Only one formula now exists, with the effects of high-speed airflow and compartment obstructions (ribs and other structure) accounted for in earlier experimentation used to derive Formula E-1. Like its predecessor for halon, this theoretical estimation formula assumes optimal distribution and mixing of the extinguishant. It is useful for preliminary sizing of systems for trade studies with other alternatives during the design process and as a starting point to begin certification tests. If a distribution system is not designed to distribute the extinguishant efficiently, certification tests may not be passed initially, and either the distribution system will require modification and improvement or the bottle capacity and extinguishant mass will need to be increased until certification is accomplished. Formula E-2 will calculate system sizes that will range between 2.3 and 4.3 times the volume of optimally designed halon systems for identical applications, with a corresponding weight growth ratio only about 80% of the volume growth ratio compared to a halon system. The estimated HFC-125 system size and weight may actually be much closer in size to an existing halon installation, due to the oversizing of many previous halon designs.

2.3.2 Design Formula

EXTINGUISHANT MASS FORMULA--FORMULA E-2

$$MASS(lb.) = 0.003166XeV + 4.138\frac{Xe}{100 - Xe}\dot{W}_{ACTUAL} \qquad \text{(E-2)}$$

Xe (from Formula E-1): engine/APU concentration for certification (Formula E-1)
V: free volume of nacelle or APU (subtracting volume due to internal components)--ft^3
$\dot{W}_{ACTUAL}$: actual maximum air mass flow rate (no experimental bounds)--lb./sec

2.4 Examples of Engine Nacelle/APU Calculations

Example I--Aircraft A

Aircraft A has an engine nacelle and an APU to be protected with a HFC-125 fire-extinguishing system. The aircraft nacelle operates with a maximum air temperature of 250°F in operations. The aircraft APU operates with a maximum air temperature of 275°F in operations. The minimum internal air mass flow rate during operations for the aircraft nacelle is 1.7 lb./sec. The minimum internal air mass flow rate during operations for the aircraft APU is 1.5 lb./sec. (It was determined to size the system conservatively by selecting the minimum air mass flow rate and the maximum air temperature. An alternative approach is shown below in Example II.) The only combustible fluid in use at the fire location in the nacelle is JP-8 whose fuel constant is 0.3586. The combustible fluids in use at the fire location in the APU are JP-8 whose fuel constant is 0.3586, and hydraulic fluid whose fuel constant is 0.4053 (when determining the concentration when multiple fluid types are present, use the higher fuel constant of the fluids present). The total volume of the nacelle is 100 ft^3; however, the clutter of 25 ft^3 reduces the free volume to 75 ft^3. The total volume of the APU is 125 ft^3; however, the clutter of 30 ft^3 reduces the free volume to 95 ft^3. Table 1 shows the relevant input data.

Table 1. Example I--Aircraft A

ENGINE		APU	
VARIABLES	GIVEN DATA	VARIABLES	GIVEN DATA
AIRT (°F)	250	AIRT (°F)	275
$\dot{W}a$ (lb./sec)	1.7	$\dot{W}a$ (lb./sec)	1.5
fuel constant (in the fire zone)	JP-8 (0.3586)	fuel constants (in the fire zone)	JP-8 (0.3586), hydraulic fluid (0.4053)
total volume (ft^3)	100	total volume (ft^3)	125
clutter (oil cooler, ducts, etc.) (ft^3)	25	clutter (ft^3)	30
free volume (ft^3)	75	free volume (ft^3)	95

Engine Nacelle

Concentration = Xe = 21.10 + 0.0185 (250) - 3.124 (1.7) + 5.174 (0.3586) + 0.0023 (250) x (0.3586) + 1.597 $(0.3586)^2$

Xe = 22.68%

Mass (lb.) = (0.003166)(22.68)(75) + (4.138)(22.68/(100-22.68))(1.7)

Mass = 7.45 lb.

APU

Concentration = Xe = 21.10 + 0.0185 (275) - 3.124 (1.5) + 5.174 (0.4053) + 0.0023 (275) x (0.4053) + 1.597 $(0.4053)^2$

Xe = 24.12%

Mass (lb.) = (0.003166)(24.12)(95) + (4.138)(24.12/(100-24.12))(1.5)

Mass = 9.23 lb.

Since the required extinguishant mass is higher for the APU and the system is designed to protect both the engine nacelle and the APU, the fire protection system must be designed to the larger mass requirement - 9.23 lb.

Example II--Aircraft B

Aircraft B has an engine nacelle to be protected with a HFC-125 fire-extinguishing system. The aircraft operates at several engine nacelle operating airflow temperatures and corresponding air mass flow rates (shown below) during the flight envelope. The corresponding concentration required is calculated for each of the airflow temperature and corresponding air mass flow rates. The combustible fluid in use at the fire location is JP-8 whose fuel constant is 0.3586. Tables 2 and 3 show the relevant input data.

Table 2. Example II.--Aircraft B

AIRT (°F)	$\dot{W}a$ (lb./sec)	Xe
115	1.0	22.26
175	1.2	22.79 *
215	1.7	22.00
220	2.5	19.60
150	2.6	17.94
125	2.1	19.02
100	2.8	16.35

Table 3. Example II--Aircraft B

VARIABLES	GIVEN DATA
fuel constant (in the fire zone)	JP-8 (0.3586)
total volume (ft^3)	85
clutter (oil cooler, ducts, etc.) (ft^3)	15
free volume (ft^3)	70

The aircraft operates at several engine nacelle airflow temperatures and corresponding air mass flow rates during the flight envelope. The corresponding concentration required was calculated for each of the air temperature and corresponding air mass flow rates. To size the system, the maximum of these concentrations should be used. Another method to determine the required concentration would be to use the overall maximum air rate and the minimum air mass flow rate during operations to give a conservative concentration estimation. Both methods are given below.

<u>Example Using Air Temperature and Corresponding Air Mass Flow Rate Which Generated Highest Concentration Requirement</u>

Concentration = Xe = 21.10 + 0.0185 (175) - 3.124 (1.2) + 5.174 (0.3586)
+ 0.0023 (175) x (0.3586) + 1.597 $(0.3586)^2$

Xe = 22.79%

Mass (lb.) = (0.003166)(22.79)(70) + (4.138)(22.79/(100-22.79))(1.2)

Mass = 6.52 lb.

<u>Conservative Estimate (Using Maximum Air Temperature and Minimum Air Mass Flow Rate)</u>

Concentration = Xe = 21.10 + 0.0185 (220) - 3.124 (1.0)
+ 5.174 (0.3586) + 0.0023 (220) x (0.3586) + 1.597 $(0.3586)^2$

Xe = 24.29%

Mass (lb.) = (0.003166)(24.29)(70) + (4.138)(24.29/(100-24.29))(1.0)

Mass = 6.71 lb.

Notice the difference of 0.19 lb. in this example between the required mass for the conservative estimate and the required mass for the estimate using the maximum operational air temperature and the minimum operational air mass flow rate. Either method is acceptable for use, with the first option requiring some additional calculations but a corresponding slight improvement in weight.

Example III--Aircraft C

Aircraft C has an engine nacelle to be protected with a HFC-125 fire-extinguishing system. The aircraft operates a maximum engine nacelle operating air temperature during the flight envelope of 200°F. The minimum internal air mass flow rate during the flight envelope for the aircraft is 1.5 lb./sec. The combustible fluids in use at the fire location are hydraulic fluid, JP-8, and oil whose fuel constants are 0.4053, 0.3586, and 0.0, respectively. For the fuel

constant, it is necessary to use the highest value relevant to the fire zone. Therefore, the fuel constant value of 0.4053 was used. Table 4 shows the relevant input data.

Table 4. Example III--Aircraft C

VARIABLES	GIVEN DATA
AIRT (°F)	200
$\dot{W}a$ (lb./sec)	1.5
fuel constant (in the fire zone)	hydraulic fluid (0.4053); JP-8 (0.3586); oil (0.0)
diameter of nacelle core (ft)	2
outside diameter of nacelle (ft)	5
nacelle length (ft)	5
total volume (ft^3) (assuming no component subtraction)	82.47
clutter (oil cooler, ducts, etc.) (ft^3)	20.62
free volume (ft^3)	61.85

$$\text{Concentration} = Xe = 21.10 + 0.0185\ (200) - 3.124\ (1.5) + 5.174\ (0.4053) + 0.0023\ (200) \times (0.4053) + 1.597\ (0.4053)^2$$

$$Xe = 22.67\%$$

$$\text{Mass (lb.)} = (0.003166)(22.6598)(61.8501) + (4.138)(22.6598/(100\text{-}22.6598))(1.5)$$

$$\text{Mass} = 6.26 \text{ lb.}$$

For the fuel constant, use the highest value relevant to the fire zone. In this case, there were three fluids used in the fire zone. The highest fuel constant (hydraulic fluid (0.4053)) was used.

Example IV--Aircraft D

Aircraft D has an engine nacelle to be protected with a HFC-125 fire-extinguishing system. The aircraft operates a maximum engine nacelle operating air temperature during the operations of 450°F. However, the air temperature must be input at a value closest to the allowable extreme (100°F-275°F) when the actual value is outside the bounds of the data. Therefore, even though the actual air temperature was 450°F, the air extreme of 275°F was used to obtain the Concentration Estimation. The minimum internal air mass flow rate during the flight envelope for the aircraft is 0.5 lb./sec. However, the air mass flow rate must be input at a value closest to the allowable extreme (0.9-2.7 lb./sec) when the actual value is outside the bounds of the data. Therefore, even though the actual air mass flow rate was 0.5 lb./sec, the air mass flow rate extreme of 0.9 lb./sec was used to obtain the Concentration Estimation. The only combustible fluid in use at the fire location is hydraulic fluid, whose fuel constant is 0.4053. Table 5 shows the relevant input data.

Table 5. Example IV--Aircraft D

VARIABLES	GIVEN DATA
AIRT (°F)	450
$\dot{W}a$ (lb./sec)	0.5
fuel constant (in the fire zone)	hydraulic fluid (0.4053)
total volume (ft^3)	150
clutter (oil cooler, ducts, etc.) (ft^3)	30
free volume (ft^3)	120

Concentration Estimation Formula = Xe = 21.10 + 0.0185 (275) - 3.124 (0.9) + 5.174 (0.4053) + 0.0023 (275) x (0.4053) + 1.597 $(0.4053)^2$

Xe = 25.99%

Mass (lb.) = (0.003166)(25.99)(120) + (4.138)(25.99/(100-25.99))(0.5)

Mass = 10.60 lb.

The air temperature must be input at a value closest to the allowable extreme (100°F-275°F) when the actual value is outside the bounds of the data. Due to statistical curve fitting technique, it is critical to input a value in that range for the validity of the curve fit. It has been observed that the extinguishing quantities at variable levels above or below this will have a marginal effect on the system size. Therefore, even though the actual air temperature was 450°F, the airflow extreme of 275°F was used to obtain the Concentration Estimation. The minimum internal air mass flow rate during the flight envelope for the aircraft was 0.5 lb./sec. However, the air mass flow rate must be input at a value closest to the allowable extreme (0.9-2.7 lb./sec) when the actual value is outside the bounds of the data. Therefore, even though the actual air mass flow rate was 0.5 lb./sec, the air mass flow rate extreme of 0.9 lb./sec was used to obtain the Concentration Estimation. However, in the calculation for the mass, **the actual air mass flow rate of 0.5 lb./sec was used**.

3.0 SUMMARY

Like the halon systems they replace, the new systems incorporating HFC-125 at this level of protection will not extinguish every imaginable fire condition created (and if so, it could not be verified via experimentation). However, much effort has gone into quantifying the level of performance of current halon systems (previously not known before other than by the review of historical mishap data) and assuring that the level of protection is preserved with new HFC-125 systems. In fact, more sophisticated techniques have emerged and are used in this design guide to better customize the design output to the particular application to prevent overdesign of systems, while retaining the general historical approach and philosophy of designing and certifying systems and using unambiguous aircraft design data as input. It is interesting to note that the halon systems as currently designed and tested in the program simulations exhibited a performance of 80 to 100% effectiveness at fielded design quantities (with historical data revealing an overall 60-80% effectiveness) for engine nacelle applications, with the HFC-125 design guidance demonstrating a validated 80-100% effectiveness (and a predicted average effectiveness statistically of at least 88%). For the dry bay application, the halon systems sized to current design procedures, as represented, demonstrated a 100% effectiveness in limited experimentation, and the HFC-125 quantities consistent with design guidance demonstrated a 95-100% effectiveness as finally configured. Systems designed using HFC-125 will generally require additional quantities to varying degrees (per application) than their halon counterparts for an identical application, **assuming an optimized halon system.** It has been found, for example, that many fielded halon systems are not optimal in sizing (as evidenced by their certification concentration and verification experiments in the test simulator), and the estimate of installing a replacement HFC-125 container has resulted in much smaller size increase impacts than may be expected. As an example of potential size impacts, the current engine nacelle design guidance published here will result in design concentrations of 14.5 to 26% by volume (depending upon the fire zone configuration), as opposed to 6% for Halon 1301. This resultant expectant increase in weight and space required has been planned and allocated for by aircraft now in design and production, but may pose challenges for those aircraft already designed for halon systems.

4.0 REFERENCES

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